The Impact of Bivariate Symbol Design on Task Performance in a Map Setting

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Abstract:
Research conducted on the theory of selective attention suggests that varying the graphic combinations used when designing bivariate symbols affects the functionality of the symbol. Some graphic combinations appear to facilitate the ability to visualize correlation between the data sets represented by the symbol; others appear to be more effective at representing the data sets individually, some even at the expense of extracting correlational information. The purpose of the research described here was to test the strength of these findings in a map use context. Several bivariate symbol designs were tested using map use tasks designed to test participants' abilities to extract either correlational or individual information. Participant reaction times provided an assessment of the types and levels of interactions that occurred with each symbol set, Results corroborate previous research in both cartography and psychology, with several symbol designs falling into each of three interactional categories: separable, integral, and configural. By confirming and expanding previous research, this study provides further evidence of the strength of selective attention theory in aiding the design of bivariate thematic maps.

Article:

INTRODUCTION

Map symbolization is most successful when a symbol's graphical format is effectively paired with its functional requirements. The challenge cartographers face is one of developing guidelines to facilitate this process. How do we match task demands with a symbol's visual dimensions to enhance map use? We already have fairly well established and tested guidelines for univariate map symbolization that build on a foundation outlined by Berlin (1083). Mersey (1990), for example, showed us that ordered colour schemes — those based on shades of a single hue or those in which hue changes are subordinate to lightness changes — work best for representing numerical data variation in general map use. Continuing this line of research, Brewer and others (1997) found that the use of spectral or hue-based schemes may also be effective for depicting numerical data when that data is rendered using a diverging colour scheme. Such thoroughly .researched sets of guidelines, however, do not currently exist to help in the development of bivariate and multivariate symbolization.

There is a substantial literature in psychology worth examining, however, that suggests that different combinations of symbol dimensions result in symbols that vary in functionality. Some appear better suited to the task of selectively attending to one dimension of the symbol; other combinations are more effective for attending to the interaction of data mapped to multiple symbol dimensions. In the research documented in this article, the capability of selectively attending to symbol dimensions was studied using several biyariate symbol sets designed with cartographic use in mind. The objectives of the study were as follows:

- to assess the functionality of these symbol sets from a, selective attention perspective
- to complete this evaluation using map tasks in a thematic map setting

- to extend a typology of graphic combinations for portraying bivariate data that originated in Nelson (2000).

Previous studies of selective attention in psychology and cartography have established a baseline from which to work, but have not attempted to test findings in a map setting. Nelson (1999, 2000), for example, tested a variety of symbol designs using standard selective attention methodology: The results established a baseline for cartographic symbols that could be compared to studies conducted in psychology. This study expands those findings by developing a methodology for testing those symbols in a thematic map setting. Findings support many of the previous studies conducted in an abstract setting and showcase the effective use of similar symbology in a tradidonal cartographic setting. The experiment presented here evaluated 15 symbol sets, including line and lettering symbolization, areal shading, dot patterns, and point symbols. Each symbol set was assessed by examining participant response times to a set of structured map tasks, which were then evaluated using a series of planned comparisons designed to target dimensional interactions in symbols.

SELECTIVE ATTENTION RESEARCH

One of the primary goals of selective attention research is to distinguish those symbol dimensions that, in combination, result in some type of perceptual interaction from those that do not. The seminal methodology for establishing this distinction is known as "speeded-classification" (Torgerson 1958; Attneave 1962; Shepard 1964). The typical speeded-classification task is built around a symbol set consisting of four symbols (Figure la) and nine sorting tasks (Figure b). Each symbol in a set consists of two visual dimensions that vary on two levels. The symbols in Figure la, for example, vary by size and by shape. The nine sorting tasks are divided among four task categories: baseline, filtering, redundancy, and condensation. Task categories vary in difficulty, depending upon whether or not participants must

- attend to only one dimension (baseline, filtering), either dimension (redundancy), or both dimensions (condensation) to correctly sort symbols
- filter out an irrelevant dimension to sort symbols using only one dimension (filtering)

During speeded-classification, participants memorize a symbol set and a rule associated with one of the nine tasks, then sort symbols that are presented to them one at a time. For the symbols in Figure la, participants may, for instance, be presented with the following sorting rule, which is associated with Baseline Task 1 (Figure 1 b): Press the left arrow key if the symbol appearing onscreen is A; press the right arrow key if the symbol is C. A more complicated rule (and, thus, a more difficult sorting task) would be one associated with Filtering Task 5: Press the left arrow key if the symbol appearing onscreen is either A or B; press the right arrow key if the symbol is either C or D. Rules are presented randomly, as are the symbols to be sorted. Each participant performs sorts for all the tasks, using a set number of symbol presentations for each task. Reaction times (RTs) are the primary data collected and used to analyse dimensional interactions. For a more thorough review of the standard speeded-classification paradigm, see Nelson (2000).

Four basic types of dimensional interactions have been noted in earlier studies (Figure 2). To describe these interactions, psychologists have developed several terms that have become commonplace in this realm of research. Separable dimensions, for example, are said to occur when three criteria are met in speeded-classification (Table 1 and Figure 2a):

- RTs for baseline and filtering tasks are not significantly different
- RTs for baseline and redundancy tasks are not significantly different
- Filtering RTs are significantly shorter than condensation RTs

Dimensions that are separable are capable of being effectively attended to independently, making them attractive cartographically for map tasks that require one to focus on individual data sets that share a common mapped space. One bivariate combination common in cartography that has displayed separable interactions in both psychological (Handel and Imai 1972; Gottwald and Garner 1975; Garner 1977; Kemmler and Smith 1979; Smith 1980) and cartographic (Nelson 1999) studies is value-size (Figure 2a). In cartography, combinations of size-hue, value-shape, .shape-hue, pie size-pie proportion, and numerousness-hue have been identified as separable in an abstract setting (Nelson 1999, 2000).

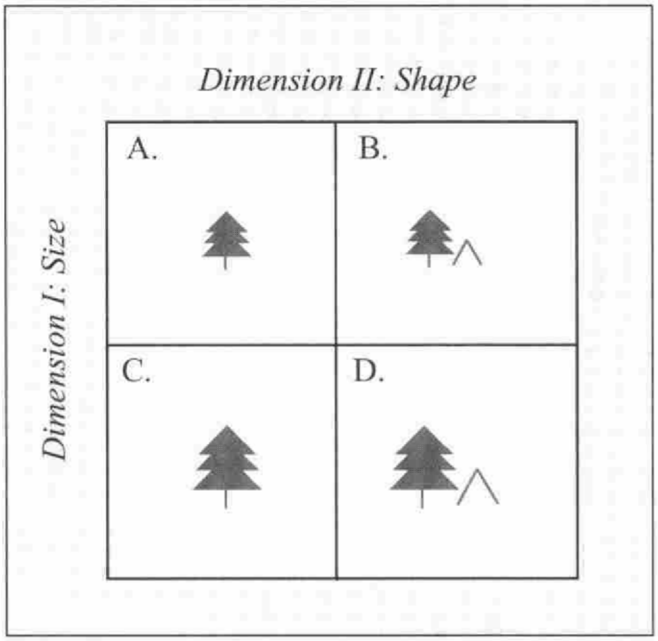
While separable dimensions facilitate selective attention, integral dimensions result in the failure of selective attention in similar tasks. Thus, if we consider interaction to be a continuum, it would be anchored on one end by separable interactions and on the other by integral interactions (Hyman and Well 1968; Garner 1974; Foarcl and Kemmler-Nelson 1984). The hallmark of integrality is interdependency; integral dimensions cannot be attended to independently. The lack of selective attention capability, however, is balanced by the ability to use the correlation of both dimensions to speed the sorting of symbols (Potts, Melara, and Marks 1998). If two symbol dimensions are found to produce an integral interaction in speeded-classification, then responses to the classification tasks meet the following criteria (Table 1 and Figure 2c):

- Baseline RTs are significantly shorter than filtering RTs (filtering interference)
- Baseline RTs are significantly longer than redundancy RTs (redundancy gain)

From a cartographic perspective, symbol sets displaying integral interactions should be useful in instances where one is most interested in having the map user extract information about the correlation of two data sets displayed in a common map space. Although cartographic studies have not reported any integral dimensions, psychological studies have noted several. Two of the most useful ones from a cartographic perspective would appear to be value-saturation (Garner and Felfoldy 1970; Gottwald and Garner 1975; Kemmler and Smith 1979; Smith and Kilroy 1979; Schumann and Wang 1980; Smith 1980) and rectangle height-width (Felfoldy 1974; Monahan and Lockhead 1977; Dykes and Cooper 1978; Dykes 1979). Examples of hese are displayed in Figure 2c.

At the midpoint of the separable–integral continuum lies the configural interaction of symbol dimensions

a. Standard speeded-classification symbol set



b. Speeded-classification task categories and associated sorting tasks

Baseline Tasks

Establishing baseline RTs when sorting 2 symbols while attending to 1 dimension, with the second dimension held constant

1. A vs. C 2. B vs. D 3. A vs. B 4. C vs. D

Filtering Tasks

Establishing RTs when sorting 4 symbols while attending to 1 dimension, with the second dimension varying randomly

5. (A or B) vs. (C or D) 6. (A or C) vs. (B or D)

Redundancy Tasks

Establishing RTs when sorting 2 symbols while attending to either dimension or both dimensions

7. A vs. D 8. B vs. C

Condensation Tasks

Establishing RTs when sorting 4 symbols while attending to both dimensions

9. (A or D) vs. (B or C)

Figure 1. An example symbol set that might be tested using speeded-classification methodology and the sorting categories and tasks used to assess dimensional interactions. (RTs = Reaction times)

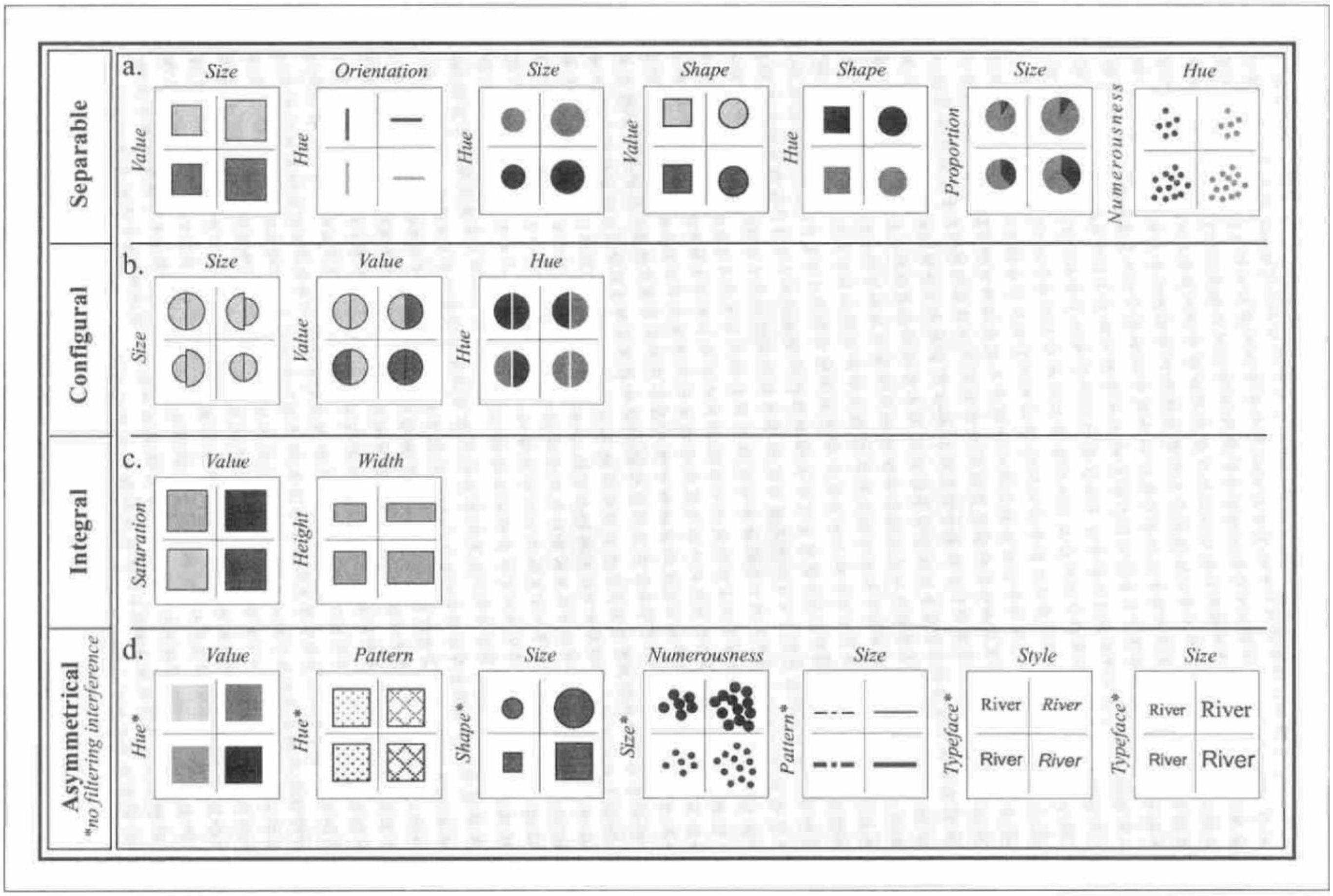


Figure 2. Examples of cartographically useful symbol sets and reported dimensional interactions from cartographic and psychological studies conducted in abstract settings. Based on studies by Garner and Felfoldy (1970), Handel and Imai (1972), Felfoldy (1974), Gottwald and Garner (1975), Garner (1977), Monahan and Lockhead (1977), Dykes and Cooper (1978), Dykes (1979), Kemler and Smith (1979), Smith and Kilroy (1979), Schumann and Wang (1980), Smith (1980), Carswell and Wickens (1990), and Nelson (1999, 2000). (From a colour original; hue differences are not apparent in the printed black-and-white version. See colour figure at www.utpjournals.com/carto/nelson2.html.)

Table 1. Speeded-classification criteria for establishing dimensional interactions

	Dimensional interactions: Significant differences		
Task comparisons	**Separable**	**Configural**	**Integral**
mean $RT_{(Baseline)}$ vs. mean $RT_{(Filtering)}$	No	Yes (Baseline < Filtering)	Yes (Baseline < Filtering)
mean $RT_{(Baseline)}$ vs. mean $RT_{(Redundancy)}$	No	No	Yes (Baseline > Redundancy)
mean $RT_{(Filtering)}$ vs. mean $RT_{(Condensation)}$	Yes (Filtering < Condensation)	Yes (Filtering > Condensation)	No

(Pomerantz and Pristach 1989). There is interference in selective attention with configural dimensions, but, Unlike true integrality, that interference is attributed to the fact that one is attending to some third dimension of the symbol to speed sorting (Potts and others 1998). This third dimension is known as an emergent feature and is formed from the "relational properties of spatially varying parts" (Carswell and Wickens 1996,. 3). In Figure 2b, the third dimension that is formed in the size-size symbol set is the perfect circle. Similar emergent dimensions exist for value-value and hue-hue, as they both produce solid circle colours that stand out on their own. Emergent dimensions should be thought of as additional codes that may provide cues about unique data conditions such as correlation. They are not visible when symbol dimensions are viewed in isolation, only when they are viewed together. In the case of configural interactions, it is believed that one may choose either to selectively attend to symbol dimensions or to use the emergent dimension to speed sorting (Carswell and Wickens 1990). Configural interactions must meet the following criteria in speeded-classification (Table 1 and Figure 2b):

- Baseline RTs are significandy shorter than filtering RTs (filtering interference)
- RTs for baseline tasks and redundancy tasks are not significantly different
- Filtering RTs are significantly longer than condensation RTs (condensation efficiency)

Several configural interactions have been noted in both psychological and cartographic studies. In almost all such interactions, the defining mark of the symbol sets is a homogeneous combination of symbol dimensions, which appears to facilitate participant perception of a third, emergent dimension. Examples of symbol sets reported as configural that may be useful to cartography include size–size, value–value, and hue–hue (Nelson 1999), Studies in psychology also report that the repeated use of a dimension, as occurs in the symbol designs above, leads to configural interactions (Garner 1978; Carswell and Wickens 1990).

It is also possible, of course, to have symbol sets that do not fall neatly into one of these three categories. Asymmetrical performance within the filtering and redundancy tasks is not uncommon and has been noted by both psychologists and cartographers (Garner 1976; Po-merantz and Pristach 1989; Carswell and Wickens 1990; Potts and others .1998; Nelson 1999). Asymmetry in redundancy tasks, for example, occurs when the correlation of two symbol dimensions enhances speeded-classification in one direction (such as positive correlation between dimensions), but correlation in the orthogonal direction (negative correlation) does not. This behaviour is believed to be caused by the use of emergent properties to facilitate sorting in one direction of correlation but not the other, and it is generally regarded as indicative of configural interactions (Pomerantz and Pristach 1989). Combinations of hue–hue and size–size both displayed this characteristic in Nelson's 1999 study, with positively correlated dimensions creating symbols that stood out over those symbols displaying negatively correlated dimensions (Figure 2b). Such behaviour could be useful if the emphasis of a map is to highlight positive correlation of data sets.

Asymmetrical filtering performance occurs when the random variation of an irrelevant dimension detrimentally affects speeded-classification for one symbol dimension but not another.

Potts and others (1998) report this type of occurrence with variations of circle size–line tilt; combinations that might be more useful for cartographic applications and have also exhibited this effect include Nelson's (1999, 2000) hue–value, hue–pattern, shape–size, size–numerousness, pattern–size, typeface–style, and typeface–size (Figure 2d). It would appear in these instances that the two dimensions that make up the symbol vary markedly in visual cue strength. Perhaps this lessens their effectiveness for displaying data correlation or for highlighting individual data sets, but such behaviour may still be useful cartographically:

> For example, when mapping a linear feature such as a stream, one might use line pattern to designate differences in stream flow (e.g., intermittent versus perennial streams), then use line size to provide secondary detail about stream order. In a case such as this, the average map-reader might not be concerned with stream order and would choose to focus on stream flow. Stream order information, however, would still be embedded in the map for those readers interested in the additional, more specific information" (Nelson 2000, 271)

RESEARCH QUESTIONS

The primary goal of this research was to extend the typology of graphic combinations, begun in Nelson (2000), that could be used to guide the development of effective bivariate symbolization for thematic maps, Nelson's 1999 and 2000 studies offer a solid foundation on which to begin building this typology, but these studies were not conducted in map setting, so they fail to answer a fundamental question crucial to laying out a robust typology: Will the results of abstract speeded- classification studies hold once symbols are placed in a map setting?

This question was examined by developing an experiment designed to test speeded-classification using map tasks. Mean response times (RTs) were collected for several carefully structured tasks designed to reflect the standard speeded-classification tasks used in an abstract setting.

METHODOLOGY

Symbol sets and maps

Fifteen bivariate symbol sets, divided into four test groups, were evaluated in the experiment (Figure 3). Sets were chosen from those tested previously in an abstract setting and represent a wide range of interactions, including separable, integral, configural, and asymmetric. One map was constructed using each symbol set (see Figure 4 for examples). Data sets varied to allow participants to evaluate multiple symbol sets within a test group without becoming overly familiar with the data. This variation resulted in the use of both real-world and fictional data sets, The regions mapped also varied and included both real-world (United States) and fictional locations.

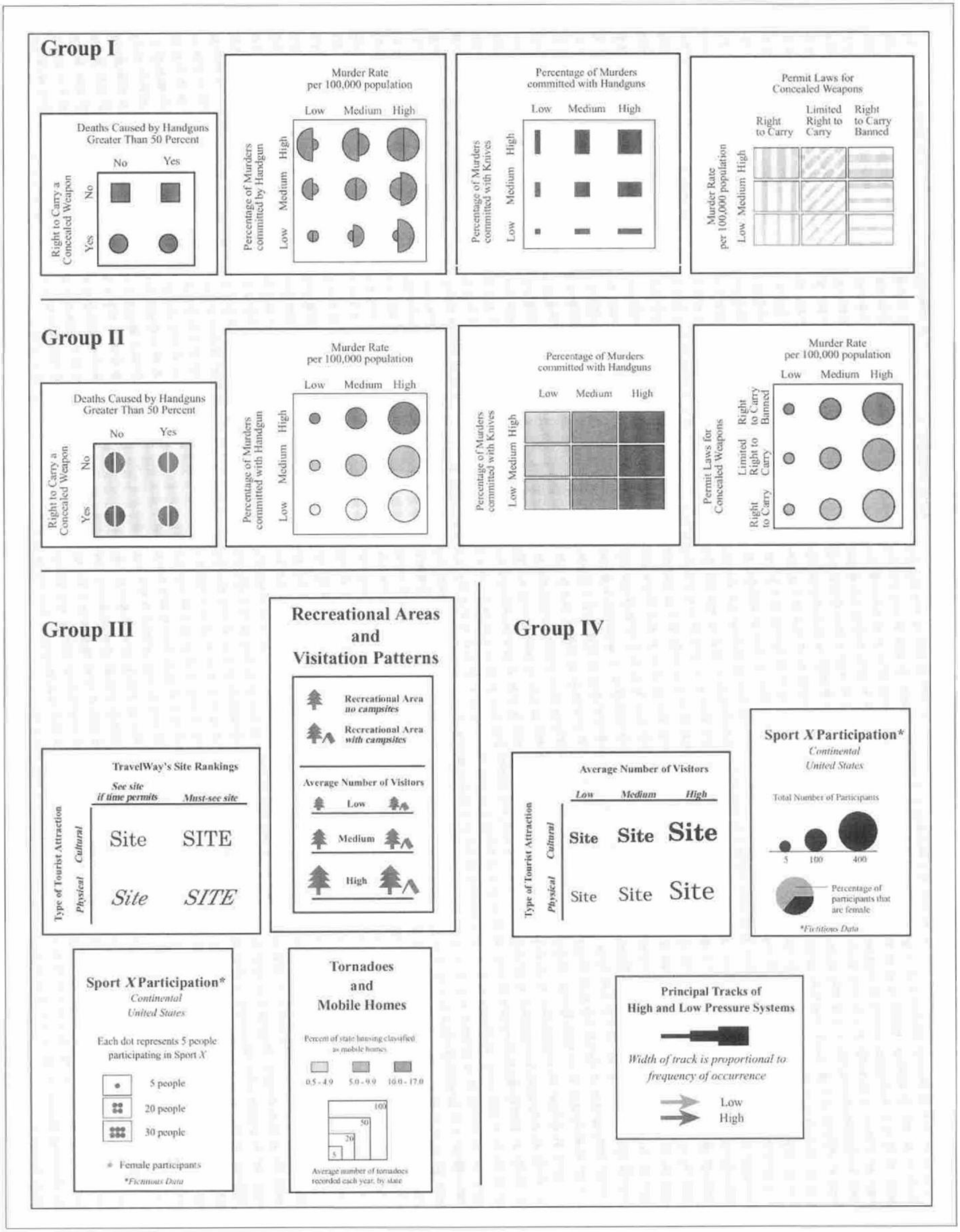


Figure 3. Legends for the 15 symbol sets tested in the experiment, divided by test group. (From a colour original; hue differences are not apparent in the printed black-and-white version. See colour figure at www.utpjournals.com/carto/nelson3.html.)

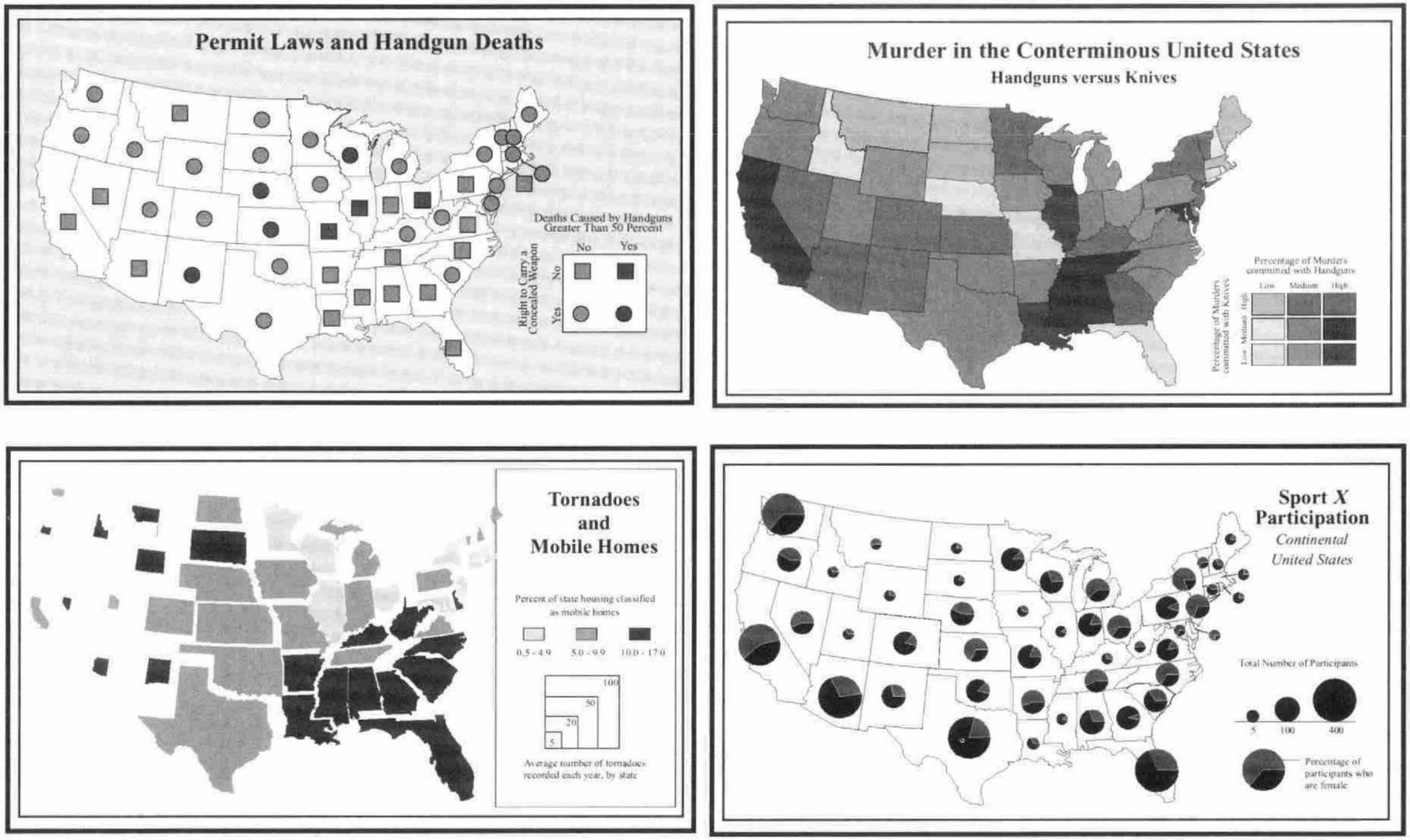


Figure 4. Examples of test maps from each of the four test groups. (From a colour original; hue differences are not apparent in the printed black-and-white version. See colour figure at www.utpjournals.com/carto/nelson4.html.)

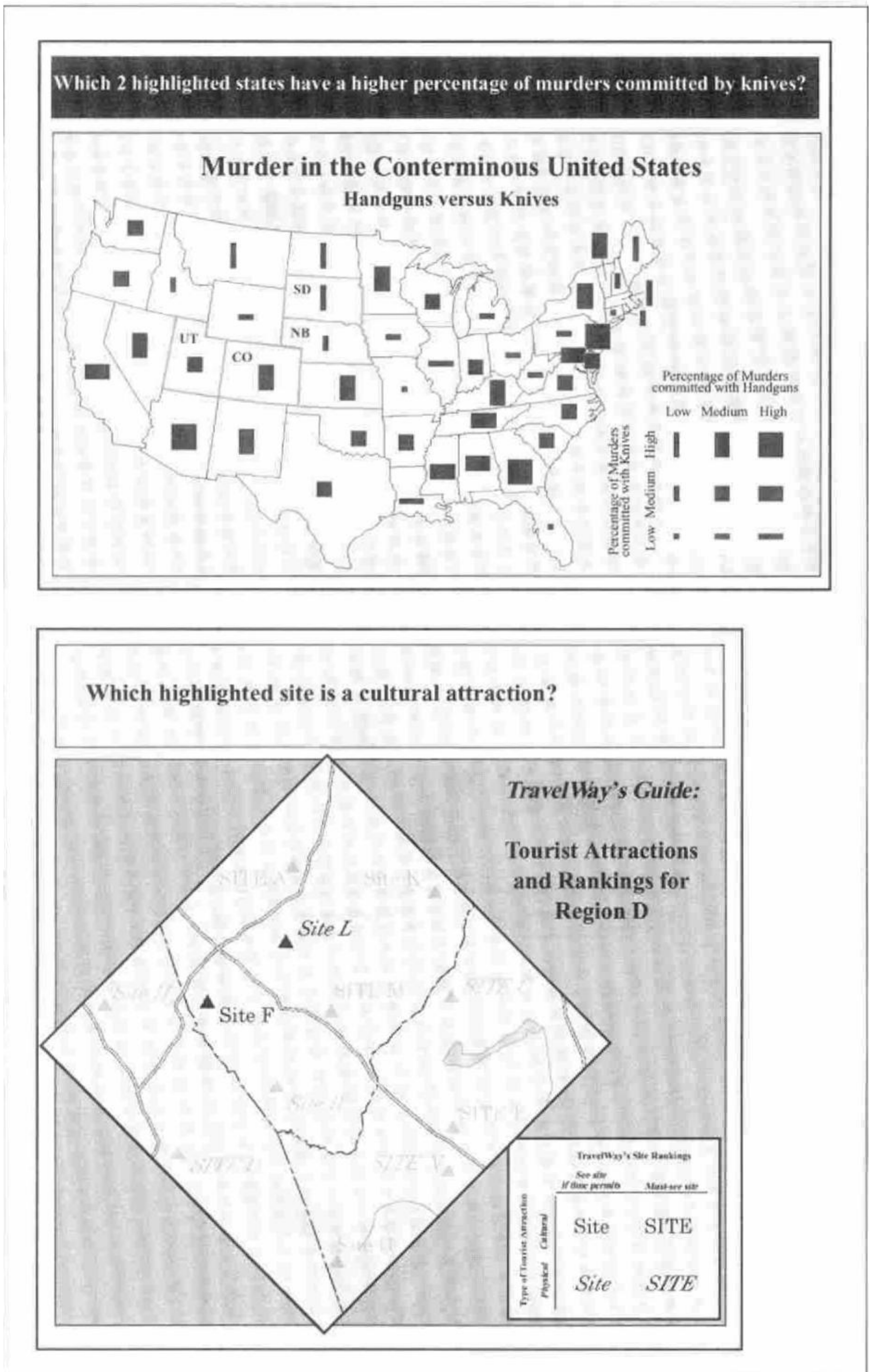


Figure 5. Examples of test maps paired with map tasks. (From a colour original; hue differences are not apparent in the printed black-and-white version. See colour figure at www.utpjournals.com/carto/nelson5.html.)

Map questions

A set of questions was prepared for each symbol set, each question requiring participants to evaluate two to four highlighted symbols on an accompanying map (Figure 5). Questions were worded so that a participant's response would be comparable to either a baseline, filtering, redundancy, or condensation task response elicited in a standard speeded-classification task. Figure 6a shows an example map legend. The symbol set derived from this legend is shown in Figure 6b. Figure 6c shows examples of test questions and their relationship to speeded-classification tasks for that particular symbol set.

Participants

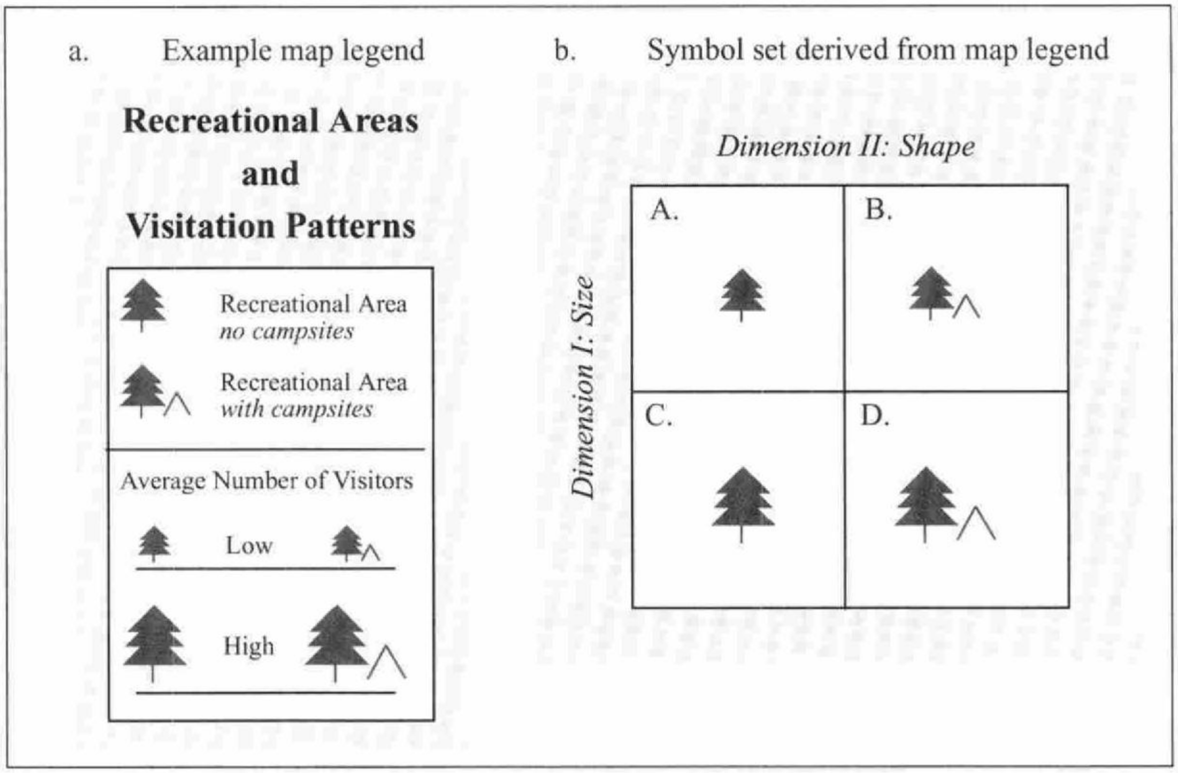
A total of 150 university students participated in the experiment. Class announcements and posted fliers were used to attract participants. Participation was rewarded with (1) class credit, (2) monetary compensation, or (3) a set of movie passes. Participants ranged from undergraduate (71%) to graduate (29%) in academic level; 65% were majoring in geography. Expertise in geography or cartography was not required to participate in the experiment.

Procedures

The experiment was computer-based and ran on a Windows NT operating system. Maps for each of the symbol sets were created using Macromedia Freehand 8.1 and exported in a graphics interchange format (GIF). The exported maps were read into a VisualBasic 5.0 program that provided the testing environment. Participants were tested individually in a controlled setting. Total test time ranged from 45 minutes to one hour.

The 15 map sets were divided into four groups; each map set within a group addressed a different topic (Figure 3). Map sets were placed into groups to ensure that maximum test time would be limited to one hour. Each participant tested was randomly assigned to one of these groups. Participants completed one block of trials for each map set in their assigned group. The order in which the map sets were seen and the order of the trials presented for each block were also randomized.

Each block consisted of a series of questions asking participants to interpret map symbols for two to four adjacent, highlighted locations. Prior to testing, participants were instructed on the concept of bivariate symbolization and completed one round of trials using a practice map set. Before beginning trials for a map set, participants examined the map legend for that set to become familiar with the symbolization with which they



c. Speeded-classification tasks and related map task examples

Baseline Task

1. A vs. C	Which labeled recreational area had more visitors?
2. B vs. D	Which labeled recreational area had less visitors?
3. A vs. B	Which labeled recreational area has a campground?
4. C vs. D	Which labeled recreational area has no campground?

Filtering Tasks

5. (A or B) vs. (C or D)	Which 2 labeled recreational areas had more visitors?
6. (A or C) vs. (B or D)	Which 2 labeled recreational areas have campgrounds?

Redundancy Tasks

7. A vs. D	With which labeled recreational area is a fewer number of visitors associated with no campground availability?
8. B vs. C	With which labeled recreational area is a higher number of visitors associated with the availability of a campground?

Condensation Tasks

9. (A or D) vs. (B or C)	With which 2 labeled recreational areas is the lack of a campground associated with fewer visitors while the availability of a campground associated with a higher number of visitors?

Figure 6. Speeded-classification tasks and related map tasks.

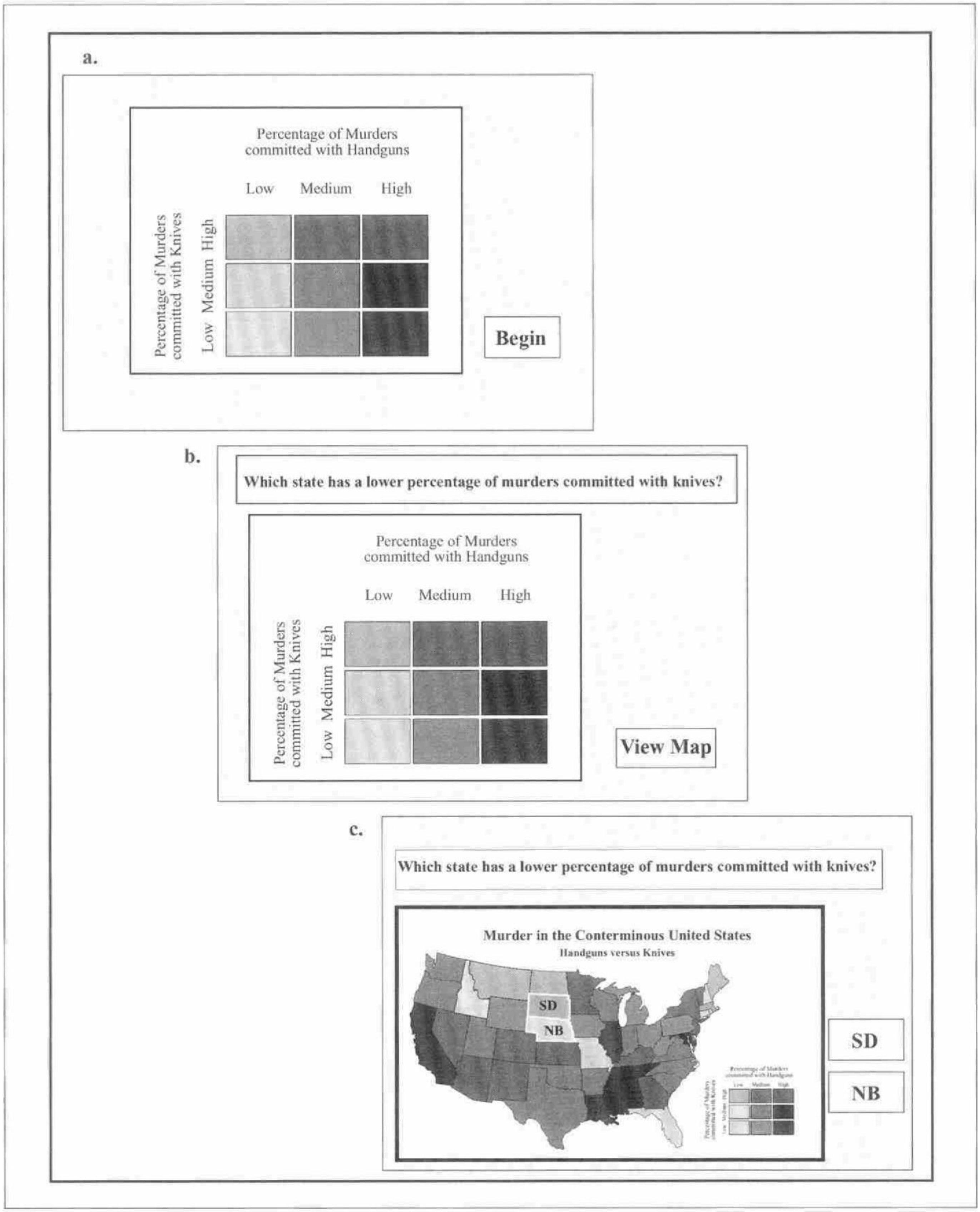


Figure 7. Example of test screens used in the experiment: (a) initial screen for studying the legend, (b) legend and test question together, and (c) timed screen with map. The initial screen was seen only once for each symbol set. Once testing began, the program looped from (b) (untimed screen) to (c) for each question. (From a colour original; hue differences are not apparent in the printed black-and-white version. See colour figure at www.utpjournals.com/carto/nelson7.html.)

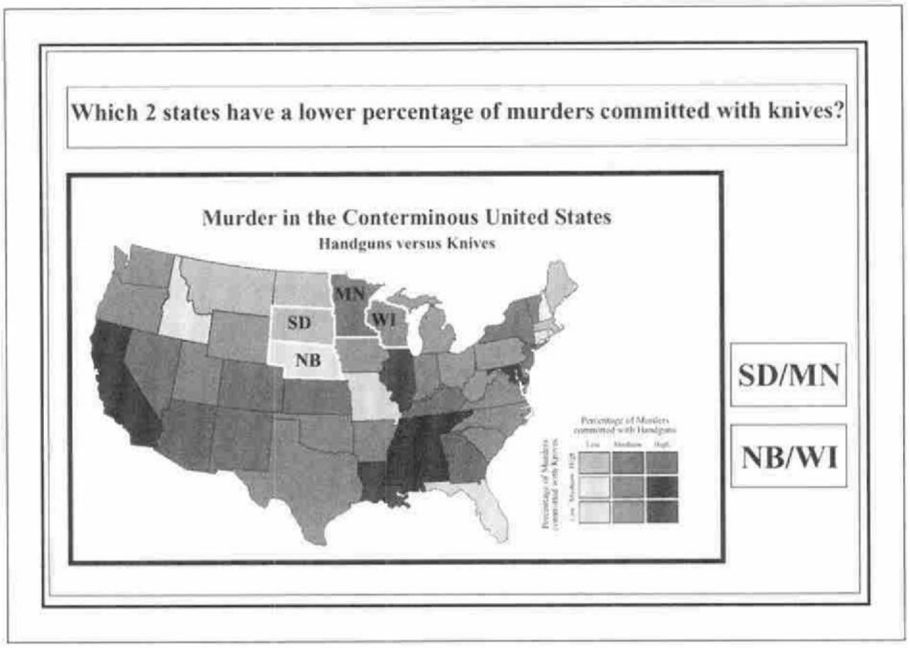


Figure 8. Example test screen for a more complicated task that requires filtering irrelevant size information to correctly answer the question. (From a colour original; hue differences are not apparent in the printed black-and-white version. See colour figure at www.utpjournals.com/carto/nelson8.html.)

would be working (Figure 7a). Trials consisted of two computer screens. Tile first screen presented the participant with a map question and the map legend (Figure 7b). Once the participant was ready to answer the question, he or she used the mouse to click on a View Map button, thus advancing to the timed screen containing the map and the question and answer buttons (Figure 7c). Participants were instructed to answer the question as quickly and as accurately as possible, once they reached this screen, by using the mouse to select the correct answer. Mouse movement was constrained to a block that enclosed the answer buttons. The initial position of the mouse was always halfway between the two buttons.

Each question posed in a set of trials was designed to test one of the classification rules used to assess dimensional interaction in a standard speeded-classification test. For example, if' the trial question was written to establish a baseline RT for one of the symbol dimensions, the participant might see a question–map combination like the one shown in Figure 7c. Here, there are two labelled states. The states have the same value but vary in saturation, and the participant is asked to choose the state that has a lower percentage of murders with knives. A more complicated example is shown in Figure 8, which asks the participant to complete a filtering task. Here the participant is presented with four labelled states where saturation and value vary for each and is asked to choose the two states that have the lower percentage of murders with knives (filtering task). Upon completing all trials for a given symbol set, participants were allowed to take a short break before beginning the test for the next symbol set. Reaction times for each symbol set were recorded for analysis.

RESULTS

Dimensional interactions for each of the 15 symbol sets were assessed using analysis of variance (ANOVA) models. Data for each symbol set were screened for incorrect and extreme responses; then a logarithmic transformation and aggregation were applied to offset the skewed nature of the distributions, a common occurrence with reaction time data. Mean reaction time (RT) was the dependent variable in each of the ANOVAS, The independent variable, map task, had nine variations - one corresponding to each of the tasks in a standard speeded-classification paradigm. A set of planned comparisons between these nine map tasks was used to assess the interactional characteristics of each symbol set (Table 1).

Figure 9a is a graph of those symbol sets whose mean reaction times for each of the map tasks indicate that the symbol dimensions are clearly separable. The cartogram size-value and the graduated symbol size-hue maps were the two whose symbol sets matched the criteria for separable interactions perfectly. RTs for baseline map tasks were not significantly different from filtering or redundancy-related map tasks, but RTs for filtering map tasks were significantly better than those for map tasks mimicking the condensation task (Table 2). The dot numerousness–hue map, graduated symbol value–size map, pictorial shape–size map, and shape–hue map did not produce perfect matches for separability, but the results were strong enough to also suggest separable interactions for these combinations (Table 3). The dot numerousness–hue and the pictorial shape–size combinations both meet all the criteria with the exception of the filtering task–condensation task comparison. In both cases, performance on filtering tasks was more efficient than performance on condensation tasks, although not significantly, resulting in a close but riot perfect fit to the standard criteria, The value–size map also does not produce filtering interference, a hallmark of separability. However, this combination deviates from the speeded-classification criteria in that RTs do not suggest poorer performance on the condensation task relative to the filtering tasks. The shape–hue map also produces a fairly nice fit to the separable criteria, with the exception of some marginal significance in one of the filtering tasks.

The remaining nine symbol sets all produced some

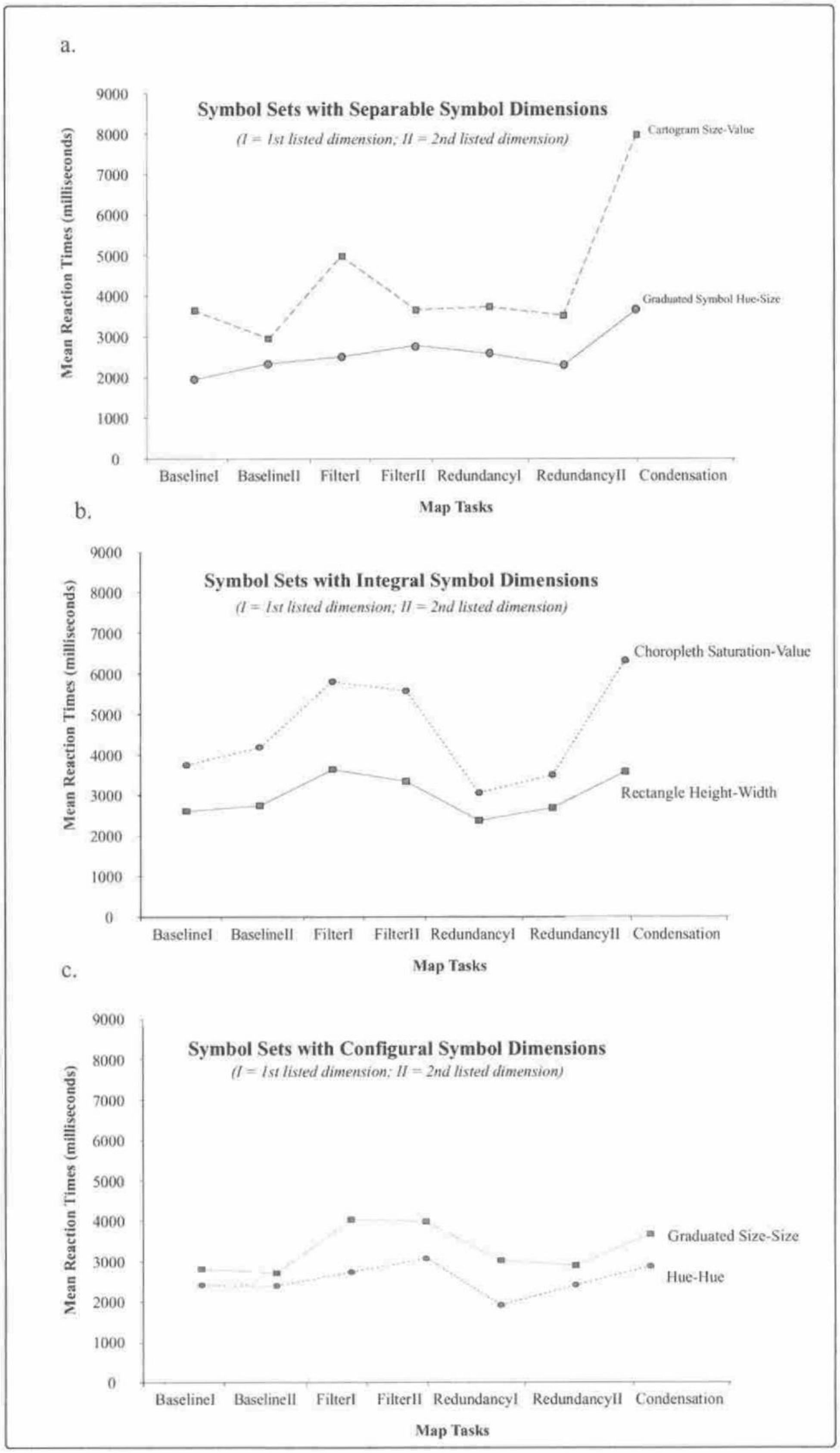


Figure 9. Plots of mean map task RTs for symbol sets meeting all the criteria for (a) separable, (b) integral, and (c) configural dimensions.

Table 2. ANOVA results for symbols matching all the criteria for separability

Symbol set	Task comparisons* and significance				
	mean $RT_{(BaselineI)}$ vs. mean $RT_{(FilteringI)}$	mean $RT_{(BaselineII)}$ vs. mean $RT_{(FilteringII)}$	mean $RT_{(Fastest\ Baseline)}$ vs. mean $RT_{(RedundancyI)}$	mean $RT_{(Fastest\ Baseline)}$ vs. mean $RT_{(RedundancyII)}$	mean $RT_{(FilteringAvg)}$ vs. mean $RT_{(Condensation)}$
Graduated symbol hue–size	(1949, 2509) **0.08**	(2336, 2786) **0.25**	(1949, 2584) **0.03**	(1949, 2290) **0.57**	(2647, 3662) **0.00**
Cartogram size–value	(3637, 4984) **0.23**	(2951, 3656) **0.62**	(2951, 3733) **0.52**	(2951, 3519) **0.78**	(4268, 7982) **0.01**

*RTs in milliseconds

Table 3. Planned comparison results for symbol sets with dimensional interactions not strictly conforming to separable, integral, or configural behaviour

Symbol set	Task comparisons* and significance				
	mean $RT_{(BaselineI)}$ vs. mean $RT_{(FilteringI)}$	mean $RT_{(BaselineII)}$ vs. mean $RT_{(FilteringII)}$	mean $RT_{(Fastest\ Baseline)}$ vs. mean $RT_{(RedundancyI)}$	mean $RT_{(Fastest\ Baseline)}$ vs. mean $RT_{(RedundancyII)}$	mean $RT_{(FilteringAvg)}$ vs. mean $RT_{(Condensation)}$
			Trending separability		
Dot numerousness–hue	(5443, 7339) **0.72**	(5525, 7495) **0.71**	(5443, 4974) **0.99**	(5443, 5896) **0.99**	(7420, 9082) **0.88**
Value-size	(2497, 3360) **0.15**	(2627, 3420) **0.18**	(2497, 2507) **1.00**	(2497, 2377) **1.00**	(3390, 3260) **0.99**
Pictorial shape–size	(2460, 3338) **0.17**	(2957, 4474) **0.05**	(2460, 2876) **0.80**	(2460, 2722) **0.97**	(3866, 4989) **0.44**
Shape–hue	(2159, 2742) **0.07**	(2455, 3086) **0.04**	(2159, 2143) **1.00**	(2159, 2028) **0.99**	(2914, 3116) **0.88**
			Filtering interference		
Choropleth pattern–pattern	(2534, 3587) **0.03**	(3198, 3344) **0.98**	(2534, 2795) **0.98**	(2534, 2604) **1.00**	(3514, 3931) **0.81**
Type form–style	(2390, 3354) **0.04**	(2305, 2907) **0.23**	(2305, 2915) **1.00**	(2305, 2296) **1.00**	(3124, 3548) **0.75**
Graduated symbol proportion–size	(4696, 7887) **0.00**	(3927, 6459) **0.00**	(3927, 4432) **0.92**	(3927, 5234) **0.17**	(7115, 8944) **0.33**
Typeface–size	(2807, 4460) **0.00**	(2668, 4239) **0.00**	(2668, 2984) **0.88**	(2668, 2641) **1.00**	(4346, 6486) **0.16**
Line hue–size	(2212, 3156) **0.01**	(2635, 4412) **0.00**	(2212, 2377) **0.97**	(2212, 2643) **0.41**	(3733, 4778) **0.33**

*RTs in milliseconds

form of filtering interference — significantly worse performance on filtering map tasks than on baseline map tasks, indicating that none of' these combinations could be considered to be composed of separable dimensions. To assess whether these symbols behave more in an integral or in a configural manner, one must further consider task performance on redundancy questions and condensation questions. Integral symbol dimensions occur when redundancy task RTs are significantly faster than baseline task RTs. In this situation, the pairing of symbol dimensions enhances one's ability to process correlational information mapped onto the symbols (Table 4). Two of the symbol sets could be classified as integral on the basis of the ANOVA analyses (Figure 9b). The value–saturation map and the rectangle height–width map both appear to be composed of integral dimensions, although neither could be said to be a classic case of integrality. Each of these cases produces asymmetric filtering interference and each produces redundancy gains, although these gains are not statistically significant.

In cases where there is filtering interference and condensation efficiency but no redundancy gains, interactions are defined as configural. These types of symbols appear to enhance correlational tasks when necessary by providing a third emergent dimension that can be used as a visual shortcut to answer these types of map questions. Both the size–size map and the hue–hue map can be classified as using configural dimensions to display thematic data (Figure 9c). The size–size map comes closest to a classic case of configurality, although the condensation efficiency obtained with the symbols is not statistically significant (Table 5). The hue–hue map provides similar results but displays filtering interference for only one of the two symbol dimensions.

Symbol sets that do not fall easily into any of these categories are the graduated symbol–proportion size map, the line hue–line size map, the pattern–pattern map, and the two maps testing typographic variations. These symbol sets produce interactions between symbol dimensions, but it is unclear, given the standard speeded-classification paradigm, whether these interactions are more configural or more integral.

DISCUSSION

Table 6 presents a synopsis and typology of the findings associated with this study. Of the 15 symbol sets tested, 10 were easily classified into one of the three interactional categories associated with selective attention. Presenting the results in this format highlights several interesting outcomes. First, six of the 10 symbol sets produce separable interactions; five of these six sets are made up of dimensional pairings that have been classified as separable in previous studies. Such results speak well of the validity of selective attention theory and its applicability to symbol design for cartographic applications. The classification of the pictorial shape–size map as consisting of separable symbol dimensions was the only real surprise for this category of interactions. Previous studies had found this combination of symbol dimensions to produce filtering interference (Nelson 1999, 2000), suggesting that the dimensions interacted during processing. It seems likely that the pictorial nature of' this symbol set, in conjunction with a map context in which the symbols were assigned meanings and surrounded by other symbols, may have influenced this effect. Perhaps being able to view all sizes of symbols while processing map tasks made it easier for participants to filter out size information when asked to answer questions pertaining only to shape variation. Likewise, being able to attach meaning to the symbol shapes may have helped in shape processing, to the extent of being able to ignore size variation when needed. Whatever the reason, this does make clear the need to confirm interactions within a map setting.

The remaining four symbol sets that produced easily classified interactions are divided evenly between the integral and configural categories. These are the symbol sets that appear to be most useful for highlighting interaction or correlation between mapped data sets. Both the rectangle height–width and the choropleth value–saturation maps enabled participants to answer questions highlighting positive and negative correlation of data more efficiently — relative to the baseline RTs of the symbol dimensions in question — than any of the other symbol sets tested. This is an interesting finding in that it provides the first cartographic confirmation of the existence of integral symbol dimensions using speeded-classification. It dovetails nicely with the work of MacEachren, Brewer, and Pickle (1998), who found evidence of the integrality of value–saturation using an alternative methodology. It also bolsters several findings in the psychological literature that suggest these symbol dimensions are integral.

The hue–hue and size–size maps, while not providing the redundancy gains associated with integrality, did apparently provide participants with a visual shortcut, or emergent visual dimension, from which they could more efficiently process correlational data while still retaining the ability to process each symbol dimension separately. These symbol dimensions have also been classified as eon figural in previous studies, so this is provides another strong argument for die viability of selective attention theory.

From a cartographic standpoint, it may also be interesting to order these symbol sets by baseline RTs to get a general impression Of the processing difficulty associated with each set. Notable here is the preponderance of hue as one of the two symbol dimensions for those sets with the shortest baseline RTs. Hue, of course, is one of the more powerful visual variables available in the cartographic arsenal, so it should not be surprising to most that these symbol sets are easier for participants to process. Also interesting are the number of point symbol sets that produced shorter baseline RTs relative to other

Table 4. ANOVA *results for symbol sets with integral dimensions*

Symbol set	Task comparisons* and significance				
	mean $RT_{(BaselineI)}$ vs. mean $RT_{(FilteringI)}$	mean $RT_{(BaselineII)}$ vs. mean $RT_{(FilteringII)}$	mean $RT_{(BaselineI)}$ vs. mean $RT_{(RedundancyI)}$	mean $RT_{(BaselineII)}$ vs. mean $RT_{(RedundancyII)}$	mean $RT_{(FilteringAvg)}$ vs. mean $T_{(Condensation)}$
Choropleth saturation–value	(3749, 5797) **0.03**	(4192, 5570) **0.25**	(3749, 3063) **0.92**	(4192, 3504) **1.00**	(5683, 6320) **0.91**
Rectangle height–width	(2605,3633) **0.01**	(2742, 3344) **0.20**	(2605, 2374) **0.97**	(2742, 2685) **1.00**	(3488, 3584) **0.99**

*RTs in milliseconds

Table 5. ANOVA *results for symbol sets with configural dimensions*

Symbol set	Task comparisons* and significance				
	mean $RT_{(BaselineI)}$ vs. mean $RT_{(FilteringI)}$	mean $RT_{(BaselineII)}$ vs. mean $RT_{(FilteringII)}$	mean $RT_{(Fastest\ Baseline)}$ vs. mean $RT_{(RedundancyI)}$	mean $RT_{(Fastest\ Baseline)}$ vs. mean $RT_{(RedundancyII)}$	mean $RT_{(FilteringAvg)}$ vs. mean $RT_{(Condensation)}$
Graduated size–size	(2875, 4139) **0.01**	(2776, 4086) **0.00**	(2776, 3095) **0.81**	(2776, 2965) **0.98**	(4104, 3774) **0.80**
Hue–hue	(2469, 2800) **0.62**	(2456, 3153) **0.02**	(2456, 1963) **0.19**	(2456, 2472) **1.00**	(3488, 2949) **1.00**

*RTs in milliseconds

Table 6. Guidelines for bivariate symbol design, using a map setting and selective attention as foundations for dimensional pairings

Dimensional interaction	Processing difficulty*							
	Less difficult							**More difficult**
Separable	Graduated symbol hue–size	Point symbol hue–shape	Graduated symbol size–value	Point symbol shape–size		Cartogram size–value		Dot numerousness–hue
Integral			Rectangle height–width				Choropleth value–saturation	
Configural		Point symbol hue–hue			Point symbol size–size			

types of symbol designs. It appears that participants found these symbol sets easier to use than bivariate choropleth maps, bivariate cartograms, and bivariate dot maps. Bivariate choropleth maps have been tested under different circumstances by other cartographers (Wainer and Francolini 1980; Olson 1981; Carstensen 1982, 1986), and, although the objectives of the experiments were different from those of this study, interpretative difficulties were noted in these instances also. Bivariate cartograms and bivariate dot maps, while presenting data in an eye-catching fashion, are both fairly unusual thematic representations and most likely suffer interpretative difficulties because of a general unfamiliarity with the display techniques.

The remaining symbol sets did not clearly fall into any one category of interaction. They also produced interactional characteristics that differed from those found in previous studies conducted ill abstract settings. The most likely explanation for differences between studies is the environment in which the speeded-classification tasks occurred. When symbols are placed in a map setting and sorting tasks are tied to specific data questions, it appears, some dimensional combinations behave differently. For example, both the graduated symbol size–proportion map and the typeface–type size map produced filtering interference in a map setting but not in an abstract environment. In addition, the filtering interference that was recorded was of an undefined nature; it was not possible to label these sets as either configural or integral under the classic speeded-classification paradigm. That some symbol sets produce such unstable results and others produce robust interactions seems to be due, at least in part, to the complexity of the symbol design.

CONCLUSIONS

The cartographic literature is replete with symbol designs for bivariate and multivariate data, but has noticeably lacked a theoretical foundation upon which symbol designs can be based. This study expanded testing of' selective attention theory by moving a classic methodology for assessing dimensional interactions into a map setting. Results very strongly favour the robustness of the theory for guiding bivariate symbol design, particularly for simpler, geometric symbol sets. Dimensional combinations can be chosen to enhance interpretation of individual data sets mapped in a common geographic space, to enhance interpretation of data correlation, or to straddle the fence by choosing combinations that may be interpreted effectively in either case, depending on need. The typology presented here is far from complete, al- though it does provide a good beginning for choosing dimensional combinations. Future research should consider the application of selective attention to some of the newer visual variables being used in interactive and animated mapping, as well as being extended to examine multivariate symbols in both traditional and newer map settings.

REFERENCES

- Atmeaye, F. 1962. "Perception and Related Areas." In Psychology: A Study of a Science, vol. 4. ed. S. Koch. New York: McGraw- Hill. 619-659.
- Bertin, J. 1983. Semiology of Graphics: Diagrams, Networks, Maps. trans. W. Berg. Madison: University of Wisconsin Press.
- Brewer, C.A., A.M. MacEachren, L.W. Pickle, and 1). Herrmann. 1997. "Mapping Mortality: Evaluating Color Schemes for Choropleth Maps." Annals of the Assmiation American Geographers 87: 411-38.
- Carstensen, L. 1982. "A Continuous Shading Scheme for Two- Variable Mapping. Cartographica 19/3: 53-70.
- Carstensen, L. 1986. "Hypothesis Testing Using Univariate and Bivariate Choropleth Maps." American. Cartographer 13: 231- 51.
- Carswell, C.M.. and C.D. Wickens. 1990. "The Perceptual Interaction of Graphical Attributes: Configurality, Stimulus Homogeneity, and Object Integration." Perception and Psychophysics 47: 157-68.

- ———. 1996. "Mixing and Matching Lower-Level Codes for Object Displays: Evidence for Two Sources of Proximity Compatibility." Human Factors 38/1: 1-22.
- Dykes, J.R. 1979. "A Demonstration of Selection of Analyzers for Integral Dimensions." Journal Experimental Psychology: Human Perception and Performance 5: 734-45.
- Dykes, J.R., and R.G. Cooper. 1978. "An Investigation of the Perceptual Basis of Redundancy Gain and Orthogonal Interference for Integral Dimensions." Perception and Psychophysics 23: 36-42.
- Felfoldy, G.L. 1974. "Repetition Effects in Choice Reaction Time to Multidimensional Stimuli." Perception and Psychophysics 15: 453-59.
- Foard, C.F., and D.C. Kemmler-Nelson. 1984. "Holistic and Analytic Modes of Processing: The Multiple Determinants of Perceptual Analysis." Journal of Experimental Psychology: General 113: 94-111.
- Garner, W.R. 1974. The Processing of Information and Structure. Hillsdale, NJ: Lawrence Erlbaum.
- ———. 1976. "Interaction of Stimulus Dimensions in Concept amid Choice Processes." Cognitive Psychology 8: 98-123.
- ———. 1977. "The Effect of Absolute Size on the Separability of the Dimensions of Size and Brightness." Bulletin of the Psychonomic Society 9: 380-82.
- ———. 1978. "Selective attention to attributes and to Stimuli. Journal of Experimental Psychology: General 107: 287-308.
- Garner, W.R., and G.L. Felfoldy. 1970. "Integrality of Stimulus Dimensions in Various Types of Information Processing." Cognitive Psychology 1: 225-41.
- Gottwald, R.L., and W.R. Garner. 1975. "Filtering and Condensation Tasks with Integral and Separable Dimensions." Perception and Psychophysics 18: 26-28.
- Handel. S., and S. Imai. 1972. 'The Free Classification of Analyzable and Unanalyzable Stimuli." Perception and Psychophysics 12: 108-16.
- Hyman. R.. and A. Well. 1968. "Perceptual Separability and Spatial Models." Perception and Psychophysics 3: 161-65.
- Kemmler, D.C., and L.B. Smith. 1979. "Accessing Similarity and Dimensional Relations: Effects of Integrality and Separability on the Discovery of Complex Concepts." Journal of Experimental Psychology: General 108: 133-50.
- MacEachren, A.M., C.A. Brewer. and L.W. Pickle. 1998. "Visualizing Georeferenced Data: Representing Reliability of Health Statistics." Environment and Planning A 30: 1547-61.
- Mersey, J.E. 1990. "Colour and Thematic Map Design: The Role of Colour Scheme and Map Complexity in Choropleth Map Communication." Cartographica 27/3: 1-157.
- Monahan, J.S., and G. R. Lockhead. 1977. "Identification of Integral Stimuli."Journal of Experimental Psychology: General 106: 94-110.
- Nelson, E. 1999. "Using Selective Attention Theory to Design Bivariate Point Symbols." Cartographic Perspectives 32: 6-28.
- ———. 2000. "Designing Effective Bivariate Symbols: The Influence of Perceptual Grouping Processes." Cartography and Geographic Information Science 27: 261-78.
- Olson, J. 1981. "Spectrally-Encoded Two-variable Maps." Annals of the Association of American Geographers 71: 259-76.
- Pomerantz, IR,, and E.A. Pristach. 1989. "Emergent Features, Attention, and Perceptual Glue in Visual Form Perception." Journal of Experimental Psychology: Human Perception and Performance 15: 635-49.
- Potts, B,C., R.D, Melara, and L.E. Marks. 1998, "Circle Size and Diameter Tilt: A New Look at Integrality and Separability." Perception and Psychophysies 60: 101-12.
- Schumann, B.C., and M.D. Wang. 1980. "Effects of Redundancy on Speeded Classification of Integral and Nonintegral Stimuli." Bulletin of the Psychonomic Society 15: 221-24.
- Shepard, R.N. 1964. "Attention and the Metric Structure of the Stimulus Space," Journal of Mathematical Psychology 1: 54-87.

- Smith, LB. 1980. "Development and the Continuum of Dimensional Separability," Perception and Psychophysics 28: 164-72.
- Smith, LB., and M.C. Kilroy. 1979. "A Continuum of Dimensional Separability." Perception and Psychophysics 25: 285-91.
- Torgerson, W.S. 1958. Theory and Methods of Scaling. New York: Wiley.
- Wainer, H., and C. Francolini. 1980. "An Empirical Inquiry Concerning Human Understanding of Two-Variable Color Maps." American Statistician 34: 81-93.

Résumé : Les recherches menées stir la theorie de l’attention selective suggèrent que de modifier les combinaisons graphiques utilisées lors de la conception d'un symbole à deux variables affecte la fonctionnalité du symbole, Quelques combinaisons graphiques semblent faciliter la capacité de visualiser la correlation entre les divers ensembles de données représentés par le symbole ; d'autres semblent être plus efficaces à représenter les divers ensembles de données individuellement et quelquefois, enléve même l' information de corrélation. Le but de cette recherche était de tester la force de ces résultats dans le contexte de l' utilisation de canes. Plusieurs types de symbole représentant deux variables ont été testés a l'aide de cartes afin d'évaluer la capacité des sujets à extraire l' information individuelle ou corrélative. Le temps de réaction du sujet fournit une évaluation du type et du niveau d'interaction engendrés par chacun des types de symbole. Les résultats corroborent plusieurs autres recherches en cartographie et en psychologie, dont plusieurs concepts de syrnbole appartiennent à l'une des trois catégories interactives soit séparable, intégrale et combinatoire. En confirmant et en ajoutant a d'autres recherches antérieures, cette étude fournit d'autres évidences de la force de la théorie de l'attention sélective comme aide à la conception de cartes thématiques a deux variables. —Diane Lacasse

Zusammenfassung Forschungsarbeiten, die sich mit der Theorie der selektiven Wahrnehmung befassen, kommen zum Schluss, dass das Variieren der Gestalt bi- variater Symbole litre Funktionsweise beeinflusst. Man- che grafische Kombinationen scheinen geeigneter zur Veranschaulichung von Korrelationen. Andere erweisen sich als wirkungsvoller bei der Wiedergabe indiviclueller Datensätze, wobei einige ihre Aussagelu-aft bezitglich Korrelationen einbüssen. Gegenstand dieser Arbeit ist es, den Gehalt dieser Forschungsergebnisse im Kontext der Anwendung von Landkarten zu fiberpnifen. Mehrere Darsteliungsmethoden bivariater Symbole wurclen im Rahmen von Karteninterpretationsfibungen getestet, um die Fähigkeit der Probanden zu untersuchen, Einsichten entweder in Korrelationen oder in den lnformationsge- halt individueller Datens:,itze zu gewinnen. Die gemess- enen Reaktionszeiten gaben Aufschluss fiber Art und Grad der Interaktionen zwischen der Testperson und dent jeweiligen Symbol. Die Ergebnisse bekraftigen frühere Forschungsarbeiten, sowohl at& dem Gebiet der Kartografie als auch in der Psychologie. Mehrere Symbol- arten konnten alien drei Interaktionskategorien zu- geordnet werden: separabel, integral und konfigural. Indetn sie frühere Forschungsergebnisse bestaigt und erweitert, liefert diese Albeit em weiteres Indiz flu die Bedeutung der Theorie der selektiven Wahrnehmung bei der Gestaltung bivariater thernatischer Karten.

Resumen Investigaciones sobre la teoría de atención selectiva sugieren que variaciones en las combinaciones gráficas usadas en el diseño de símbolos bivariables afectan la funcionalidad del símbolo. Algunas combinaciones parecen facilitar la visualización de la correlación entre los conjuntos de datos representados por el simbolo; otras son más efectivas en la presentación individual de conjuntos de datos, a veces a expensas de información correlacional. El propósito de esta investigación fue comprobar la robustez de estos resultados en el uso de mapas. Varios diseños de simbolos bivariables fueron sometidos a pruebas de uso de mapas que evaluaron la habilidad del sujeto de extraer información correlacional o individual. El tiempo de reacción del sujeto sirvió como evaluación del tipo y nivel de interacción que ocurrió con cada grupo de simbolos. Los resultados corroboran investigaciones previas tanto en cartografia como en sicologia,